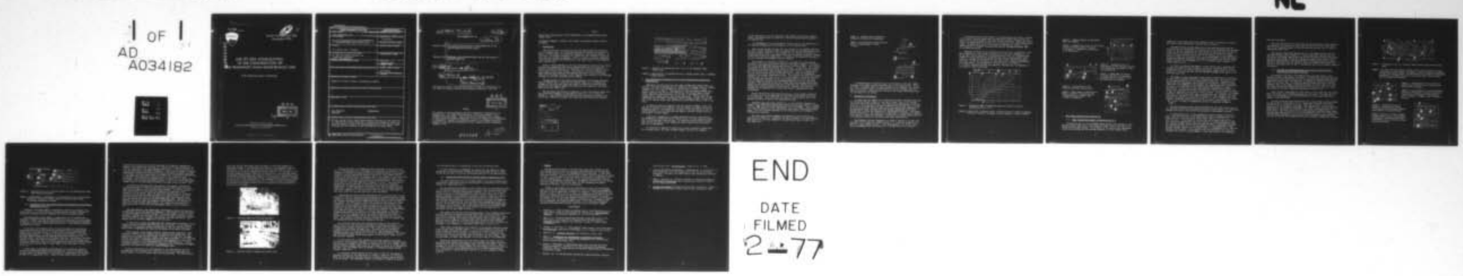

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Draft Translation 560
December 1976

USE OF SOIL STABILIZATION IN THE CONSTRUCTION OF THE FRANKFURT/MAIN RAPIDTRANSIT LINE

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COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Draft Translation 560

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): USE OF SOIL STABILIZATION IN THE CONSTRUCTION OF THE FRANKFURT/MAIN RAPID TRANSIT LINE

5. TYPE OF REPORT & PERIOD COVERED: Translation

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): E.W. Schultz and J. Dintzner

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS: U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

12. REPORT DATE: December 1976

13. NUMBER OF PAGES: 16

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

SOIL STABILITY
INJECTION
CONSTRUCTION

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(14) CRREL-TL-560 (12) 19p.

DRAFT ~~TRAN~~SLATION 560

(11) Dec 76

(6)

ENGLISH TITLE: USE OF SOIL STABILIZATION IN THE CONSTRUCTION OF THE FRANKFURT/MAIN RAPID TRANSIT LINE

FOREIGN TITLE: (ANWENDUNG DER BODENVERFESTIGUNG BEIM BAU DER S-BAHN IN FRANKFURT/MAIN),

(10) Ekkehart seph

AUTHOR: [redacted]W. Schultz [redacted] Jo Dintzner

(21) Trans. of

SOURCE: Die Bautechnik, [redacted] v52 [redacted] p37-42 1975

(West Germany)

Translated by Office of the Assistant Chief of Staff for Intelligence for U.S. Army Cold Regions Research and Engineering Laboratory, 1976, 16p.

NOTICE

1473

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K-6774

USE OF SOIL STABILIZATION IN THE CONSTRUCTION OF THE FRANKFURT/MAIN RAPID TRANSIT LINE

By Engineer Ekkehart W. Schultz, Bad Vilbel, and Engineer Joseph Dintzner, Wiesbaden

1. Introduction

The stabilization of unfixed soils by the force-injection of binders into the ground pores, with the broad spectrum of injection instruments and means, is today a part of conventional underground construction methods. In this way it is possible frequently to achieve not only technical simplifications but also economic advantages. This is a report on the soil stabilization work done during the construction of the first section of the Frankfurt rapid transit line.

Here it became necessary to use soil stabilization because of the typical construction underground structure in Frankfurt/Main with its sandy and gravelly covering layers above the "Frankfurt clay" which are pierced or cut by the rapid transit line tunnels. The tunnels in the area considered go under important and sensitive above-ground structures, such as the track yard and the terminal buildings of the Frankfurt main station or the buildings standing in the entire railroad station quarter.

The main purpose of the stabilization measures, in the cases described below, primarily was to stabilize the unfixed layers and to increase the strength of the loose rock above the tunnels to secure the existing above-ground structures against damage resulting from the formation of the half-space due to the tunnel work.

The following contribution to questions of soil stabilization deals with the construction examples in construction block S 2, S 4, S 5, and S 6 (Figure 1). This revolves around questions and viewpoints relating to the use of soil stabilization under local conditions and construction methods.

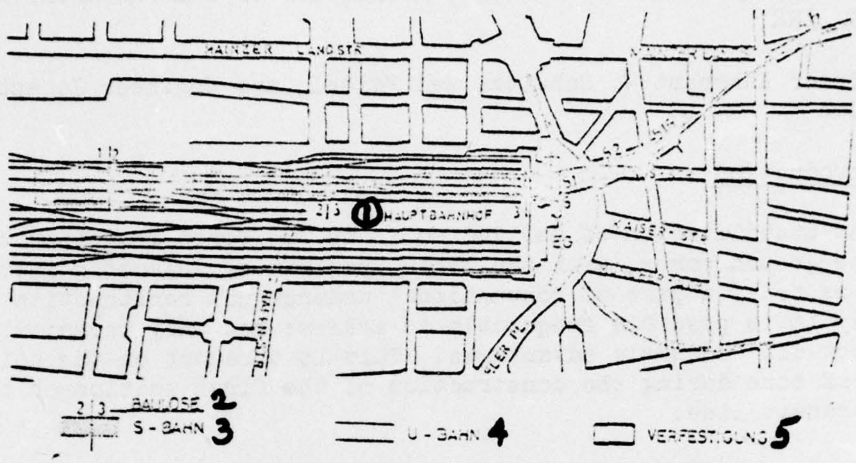


Figure 1. Overview of Construction Lots 1 to 6 of the Frankfurt Rapid Transit Line.

Legend: 1--Main Station; 2--Construction Lot; 3--Rapid Transit Line; 4--Subway; 5--Stabilization.

2. Soil Stabilization--Viewpoint on Its Action Mechanism and Application Possibilities

Basically, one can inject all soil types through which water flows. In practice, the area of application, for technical and economic reasons, however, includes only soils with permeability coefficients of 10^{-1}m/s to about 10^{-6}m/s (4, 5, 6, 8, and 9). The spectrum of injection agents extends from cement (possibly with sand or other additions) via colloid cement, respectively, Bentonite cement mixtures, all the way to the chemical solutions (mineral gels, organic resins, and bitumen emulsions). In the light of past experience, one can expect considerably higher strength figures in case the soil to be treated reveals high permeability coefficients than in case of low ones.

In terms of injection capability and the required strength, every soil type can be matched up with specific injection agents in connection with the economical aspects. The expenditure in terms of cost and time go up due to higher material costs and declining performance, the more closely we get to the chemical injection agents.

A decline in permeability is always connected with soil stabilization. The permeability coefficient can be reduced by up to 10^{-4}m/s and more according to investigations conducted here. In large-area stabilization projects, this can have an effect on the underground water conduit and volume which must not be disregarded.

If injection is expected to result not so much in greater strength than in a sealing effect, then high strength figures, such as, for example,

in dam construction, are not required or may perhaps be undesired whenever plastic deformations must be accepted in the soil treated without damage to the sealing body.

If the emphasis is on stabilization, then we come to the question as to the required strength and the deformation of the injected body.

Here it must be kept in mind that the strength of the injected material may have entirely different causes in keeping with the individual agents used. In case of cement injections, the strength, as in concrete, is based on a chemical-physical bond of the cement stone with the additive material, whereas in the case of gels and suspensions it is based on the gluing and bracing of the soil drainsby the hardened injection material.

The strength of chemically treated soil is based not on the inherent strength of the injection material--which is very small compared to concrete--but on the above-mentioned gluing and bracing of the soil drain. As a result the unfixed soil gets the cohesion which it lacks. In addition, the friction resistance is increased due to the intensive intertwining of the soil bodies and the restriction of their movement possibility. Here it is important to fill up the soil pores as much as possible and to insure the homogeneous soaking of the planned stabilization body. This requires an injection pressure betweem 5 and 30, ato; this is why it will be necessary to examine very carefully whether such pressures can at all be permitted in view of the condition of superposed material and the swelling sensitivity of the structures involved. Here of course we must not forget that this pressure exists only locally at the injection point and that it declines very rapidly as we move further away from the injection lance [stake]. Besides, the injection pressure can be regulated via the injection speed in keeping with local requirements.

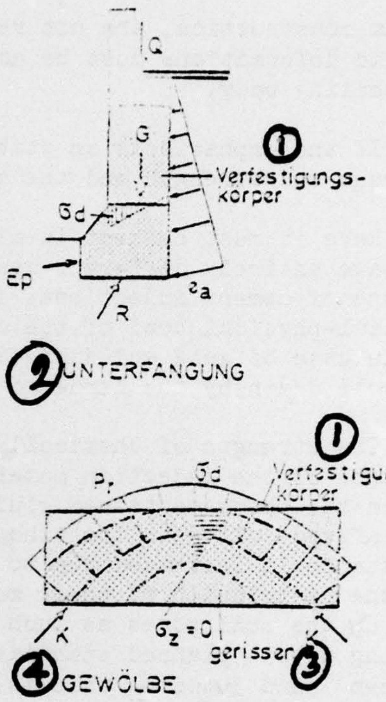
Before tackling any stabilization projects, we must address ourselves to the question as to the magnitude of the stress to be placed on the soil to be stabilized. Only if we know the limits of stabilization will it be possible correctly to mention the stabilization body.

Depending upon the author involved (4, 7), the bending strength, for example, in a construction underground stabilized with gel, come out to about 0.10-0.15 σ_d while the thrust resistance is 0.30-0.35 σ_d. Statis systems with traction stresses in the stabilization body require considerable dimensions. The type of stress inherent in the stabilized soil is primarily represented by pressure.

Thus wall-like pressure members and especially arches [vaults] are suitable here (Figure 2). Regardless of what the shape of the stabilization body looks like, the vault adapted to the particular type of stress will take shape in it.

Figure 2. Possible Statis Systems in Stabilized Construction Underground.

Legend: 1--Consolidation [Stabilization] Body; 2--Underpinning; 3--Torn; 4--Vault.



In dimensioning an injection vault, we must keep in mind that higher pressures occur under the arch abutments due to the tension shift. If the soil which is exposed under the arch abutment can be deformed, then settlement will develop in spite of stabilization and this, together with the elastic and plastic deformations of the arch, can assume considerable overall settlement in the terrain.

3. Construction Underground

To understand the example of a construction project discussed below and the individual measures taken in this case, we must first of all quickly review the local soil conditions. The construction underground in construction lots 1 to 6 consists in filled-up layers which are less than 3.0 m and up to 8.0 m thick and which are made up of sandy and gravelly sediments of the Quaternary (Main terrace) with the natural underground water level. Beneath that, we have the formations of the Frankfurt Tertiary. The characteristic structure of the construction underground is illustrated in Figure 5. This figure of course does represent a cross-section through construction lot 2 but basically applies to the entire area under consideration.

The Frankfurt Tertiary commences at a depth of between 6.0 m and, here and there, 11.0 m under the present terrain. It is made up primarily of strata of rigid "Frankfurt clay." This highly plastic clay is not injectable with permeability coefficients of $k = 10^{-8}$ m/s up to $k = 10^{-11}$ m/s.

The boundary surface with respect to the Quaternary cover layers, because of its origin, reveals undulations and depressions which remain filled with water also if the groundwater level were to drop [subside]. These cover layers consist of medium sand all the way up to coarse gravel with alternating percentages. The granulation band of the layers is indicated in Figure 3. The stratification is strongly pronounced and extends from uniform medium sand up to nonuniform gravel.

Important criteria in the injectability of soils are, in addition to the grain composition, their deposit density as well as their permeability. As we can see from the results of the ram probes with the U. S. Standard Probe (Figure 4) we are dealing here primarily with loose to medium-dense soils which are suitable for stabilization with gels or more thin-flowing agents and which, in some of the layers, at best, are still suitable for stabilization with cement. The permeability coefficients of $k = 10^{-2}$m/s to $k = 10^{-6}$m/s, determined during the pump test, characterize the framework of the injection agents mentioned.

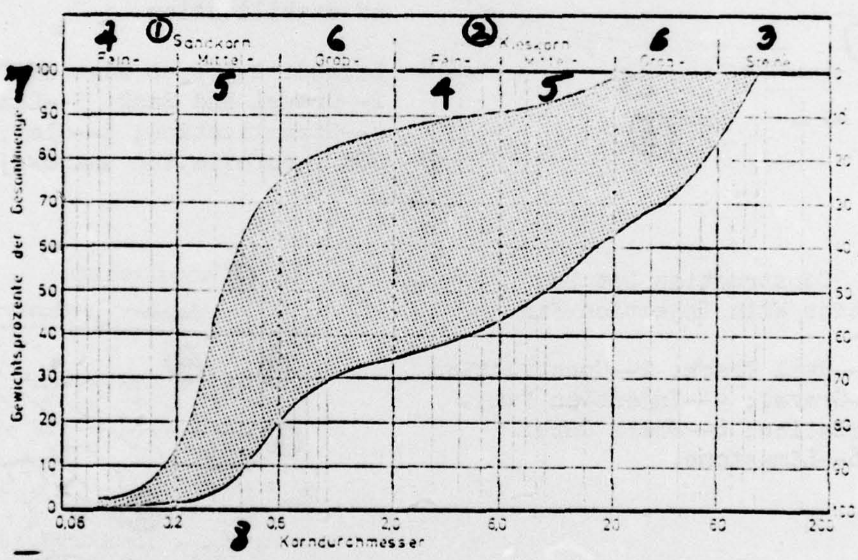
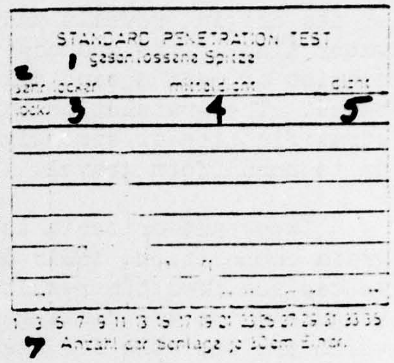


Figure 3. Granulation Band of Quaternary Sands and Gravels in Area of Construction Lots 1 to 6.

Legend: 1--Sand Grain; 2--Gravel Grain; 3--Stones [rocks]; 4--Fine; 5--Medium; 6--Coarse; 7--Percent by Weight of Total Quantity; 8--Grain Diameter.

Figure 4. Deposit Density of Quaternary Marls and Gravels.

Legend: 1--Closed Point [tip]; 2--Very Loose; 3--Loose; 4--Medium Dense; 5--Dense; 6--Frequency; 7--Number of Strokes per 30 cm Penetration.



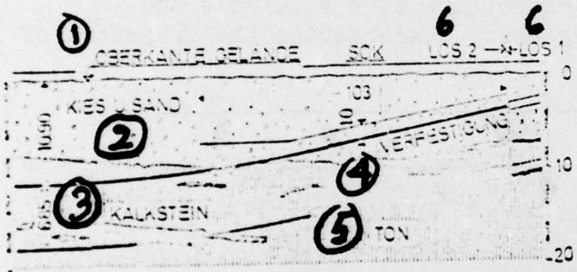
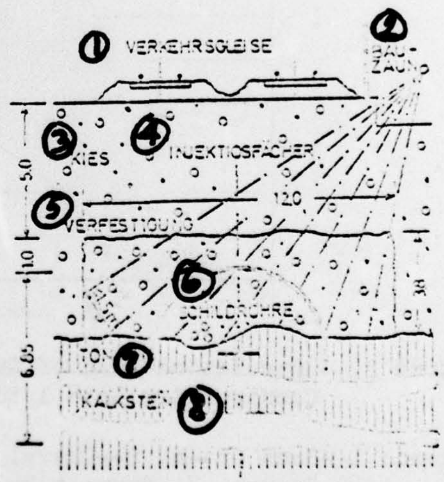


Figure 5. Construction Lot 2c, Longitudinal Profile Through Construction Underground and Tunnel in Area of Stabilization.

Legend: 1--Upper Edge of Terrain; 2--Gravel and Sand: 3--Limestone; 4--Stabilization; 5--Clay; 6--Lot; SOK [abbreviation unknown].

Figure 6. Construction Lot 2c, Cross-Section With Injection Fan.

Legend: 1--Rail Track; 2--Construction Fence; 3--Gravel; 4--Injection Fan; 5--Stabilization; 6--Shell Cube; 7--Clay; 8--Limestone.



4. Soil Stabilization Project Carried Out

4.1. Shell Construction Method, Construction Lot S 2

Construction Lot 2 of the Frankfurt Rapid Transit Line consists of four parallel tunnel tubes with a total length of about 1,450 m which had to be driven with the shell method. On the basis of the construction underground conditions described and the existing gradients, all four tunnel tubes,

coming out of the stable and rigid "Frankfurt clay," increasingly intersect the loosely deposited gravelly covering layers (Figure 5).

One particularly critical phase in the shell-driving method was the 40-m long zone of intersection of the shell roof with the gravel-clay boundary because it was not impossible that there might be surprises here in terms of local, groove-like depressions in the clay filled with gravel and water. Neither in this sector nor in the rest of the section up to lot boundary 2/1, could one figure, in the natural soil, on the development of bracing vaults, because the constant vibrations from heavy train traffic and the roof [head] covers of only 0.5 to a maximum of 1.0 D (D = outside tunnel diameter) no longer permitted this.

In order to eliminate any danger to train traffic due to possible soil collapse and damage to and blocking of the heavily frequented main switch connections due to intolerable terrain settlement, plans called for the stabilization of gravels and fans from the Tertiary boundary to at least 1.0 m above the shell roof.

The danger of major settlement arises without stabilization by virtue of the fact that an uncontrollable soil withdrawal can occur, at the face, due to the missing stability of the construction underground. Experience has showed that the ring-shaped crack between the soil and the tubbing [casing] closes due to the sagging of the unstable soil immediately after leaving the tail end of the shell and can no longer prevent the pressing of these settlements. In the case at hand, stabilization therefore was intended to form a vault cap above the tunnel cross-section to be driven forward in order to make it impossible for the soil to fall in after. To determine the strength required in the provided vault caps, investigations were conducted on a twin-joint arch on the basis of the deposit conditions. This estimate, with the planned tube pressure resistance of 15 kp/cm^2, in case of symmetrical loading [stress], depending upon the cross-section, yielded a safety figure of ν = 1.5-3. In case of unsymmetrical stress, it generally dropped to $\nu < 2$.

The key formations--which were determined after the shell was driven, in the stabilized area--with the exception of places where special soil conditions created difficulties, were within the framework of measurement accuracy.

In construction lot 2 it was necessary to stabilize about 13,000 m^3 of soil. The cross-sections of the stabilization bodies, depending upon the depth position of the individual tunnel tubes, were 2.5 m x 10.0 m to 8.0 m x 12.0 m. On the basis of the cost and the strength required for the soil conditions encountered, gels were injected on a sodium-waterglass base. The required strength figures were attained and partly considerably exceeded. The fluctuations were due to the heterogeneity of the underground because uniform strength figures can be achieved only in a homogeneous soil. When the strength was too great, it was possible that the stabilized soil could be separated only with the mining hammer in individual zones in the subsequent

shell-driving phases.

The stabilization work was done from the terrain because, under existing circumstances, the execution of this work from the front of the face would have led to successive delays in the shell-driving time and thus to considerable additional costs.

The injection bore holes were driven in a fan-shaped pattern from the available working surface (Figure 6). Sleeve pipes were inserted into the bore holes and through them the gel was injected during the second work phase following a preliminary injection (closing the larger vacuum spaces) with a Bentonite cement mixture. The pressing work was accomplished from an automatically operating injection center in which all phases--starting with the dosing of the mixture all the way to introduction into the soil--were controlled and watched.

4.2. Securing the Terminal Building of the Main Railroad Station, Construction Lot 4 and S 5.1/U 28a

The terminal building of the Frankfurt main railroad station, built around the turn of the century, consists of a central main hall with the main exit and the ticket windows as well as the laterally adjoining wings with the commercially used rooms. The main hall is spanned by a barrel arch [vault] which, on the front side, is limited by massive sandstone arches. The soil mechanics test of the tunnel construction methods in Lot S4 and Lot S 5.1/U 28a (open construction method) revealed that one could not rule out a one-sided shift of the hall foundations amounting to about 4.0 cm.

After a static investigation of the vaults, it was found that the shifts which the vaults could withstand amounted to only about 2.5 cm and that, in view of the settlements which were determined at 4.0 cm, there would be a danger to the hall arches.

In view of the adjoining construction pits, and to form a strong abutment for the struts of construction lot 5.1, plans here therefore called for a stabilization of the gravels and sands, which extend down to 11.0 m below ground, as of the foundation underedge. The required cubic strength had been established at 25 kp/cm^2 on the basis of the static investigations of the earth [dirt]. The injections, for the above-mentioned strength target, were likewise performed here with gel on a soda-waterglass base. The stabilization was performed, depending on the locality, from the partly dug-out construction pit as well as from basements and from the terminal [reception] building.

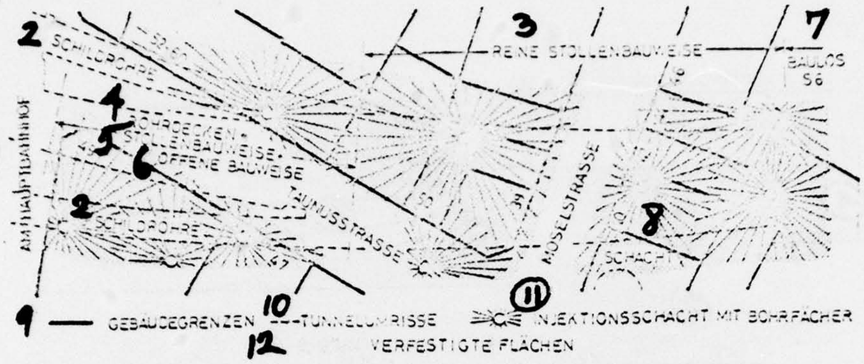


Figure 7. Construction Lot 5.2, Overview, Stabilization Zones With Drilling Fans.

Legend: 1--On Main Railroad Station; 2--Shell Pipe; 3--Pure Gallery Construction Method; 4--Pipe Covers [ceilings]; 5--Gallery Construction Method; 6--Open Construction Method; 7--Construction Lot; 8--Shaft; 9--Building Boundaries; 10--Tunnel Outlines; 11--Injection Shaft With Drilling Fan; 12--Stabilized Surfaces.

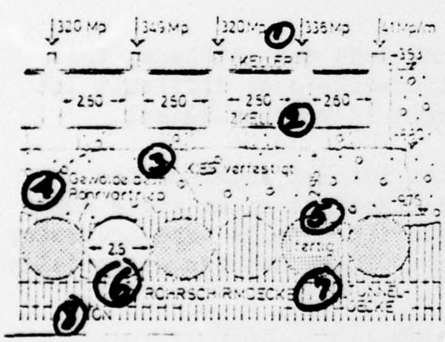
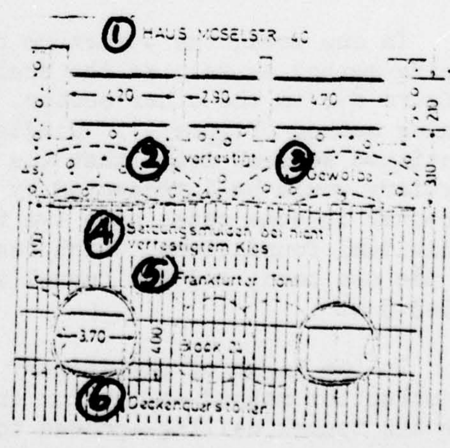


Figure 8. Construction Lot 5.2, Protective Injection for Pipe-Driving of Southern Pipe Shield Cover [ceiling].

Legend: 1--First Basement; 2--Second Basement; 3--Gravel, Stabilized; 4--Vaults During Tube [Pipe] Drive; 5--Finished; 6--Pipe Shield Cover [ceiling]; 7--Tunnel Cover [ceiling]; 8--Clay.

Figure 9. Construction Lot 5.2, Formation of Equalization Walls During Gallery Drive Through Chemical Stabilization of Sand and Gravel.

Legend: 1--House at 40 Mosel Street; 2--Stabilized; 3--Arch; 4--Settlement Depression in Non-Stabilized Gravel; 5--Frankfurt Clay; 6--Lateral Ceiling Gallery [galleries].



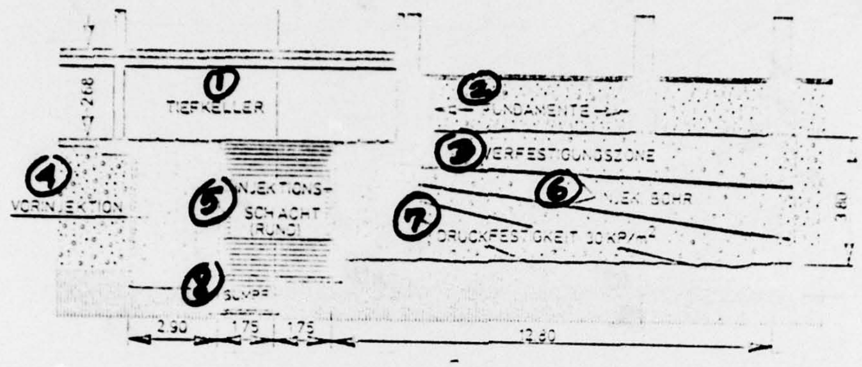


Figure 10. Construction Lot 5.2, Injection Shaft IS 5 and Stabilization Body Under Existing Buildings.

Legend: 1--Sub-Basement; 2--Foundation; 3--Stabilization Zone; 4--Preliminary Injection; 5--Injection Shaft, Round; 6--Injection Bore Holes; 7--Pressure Resistance; 8--Sump.

4.3. Type Shield Cover Construction Method and Mining-Style Undercutting, Construction Lot 5.2.

Because of the large number of construction methods and problems, this construction lot is the technically and construction-wise most difficult lot among those considered and will therefore be covered in greater detail.

The rapid-transit line tunnels in construction lot 5.2 undercut the buildings on Taunus and Mosel Streets because the lines run at an acute angle (Figure 7). This is why several different construction methods were necessary in combination with the trumpet-shaped ground plan. These methods essentially characterize two areas.

In one area, the structure had to be built according to the open and mining method as well as the shell and pipe shield cover [ceiling] method (Figure 8); in the other sector, it could be put up exclusively with the mining method (Figure 9). Gradients and construction heights in the first-mentioned segment meant that the sandy-gravelly covering layers of the Tertiary would be intersected by the tunnel structure. The undercut buildings moreover in some cases have two basements so that the intervals between the individual foundations, which rest on the gravel and which are heavily stressed, on the one hand, and the tunnel's upper edge, on the other hand, is only 2.5-3.5 m.

In the light of preliminary investigations, the technically feasible construction method--and, under existing conditions, the most economical one for the tunnel ceiling--proved to be the method of underpinning the building by means of the tube shield cover. Under the tube shield cover, the floor

and the walls were then to be built according to the gallery construction method, to the extent that they were not located in the open construction pit. With the tube shield cover underpinning method alone, it was not possible to rule out unfavorable settlement differences. Apart from the danger of leaking water-gravel mixtures and uncontrollable soild withdrawal during the driving of the pipes, one could expect major settlement due to the elastic deformations of the pipes resulting from the direct action of the foundation loads [stresses]. The calculation, depending upon the bedding of the pipes, from this aspect alone reveals settlements between 1.5 and 4.5 cm which immediately became a part of the differing settlements with angle twists of about 1:100.

To avoid the previously described possible settlements [subsidences], it became necessary to stabilize the gravel and the sand between the under-edges of the foundation and the gravel-clay boundary. It was the purpose of this stabilization, to facilitate the formation of a protective wall (Figure 8), in the gravel, above the particular pipe that was to be driven. The pipes were driven one after the other at a certain rhythm so that the protective arches over the just-finished pipe [tube] were destroyed again while the arches were built up over the neighboring pipes. Because of the numerous load shifts under the formation of new arches, it was necessary to carry out a large surface stabilization. The success of this measure is characterized by the fact that the settlements later on did not exceed 1.2 cm.

The same applied to the second area, specifically, to the construction of the galleries in the ceiling level (Figure 9). Here however it was impossible to avoid settlement due to the cutting of the gravel layers; instead, it was possible to achieve the leveling of the overall settlement depressions through the arch formation above the particular gallery that had been driven. This applies also to the shell segments in the first area.

At this point it might be emphasized that large-surface settlements in the tunnel construction method used here could not be avoided. It was therefore necessary in all phases of tunnel construction to keep the differing settlements within a magnitude that would not be harmful to the nearby buildings.

Model studies on the arches revealed a required cubic compression resistance of 30 kp/cm^2, on the average, for the entire stabilization area. The production of an injection plate failed in spite of 4.0 m and more thickness because the attainable traction, presses, and shear resistance of the stabilized soil was only small. Prestressing this plate was impossible for these same reasons and because of the creep capability of the injected gravel. The most economical method for stabilization--in combination with the required strength--again was the injection of gels on a soda-waterglass base.

In this construction lot, the execution of the stabilization was very problematical; this involved about 19,200 m^3 of soil to be stabilized on a ground surface of 4,800 m^2 mostly under existing buildings. The stabilization

above the vertical bore holes from the terrain or from the basement was impossible because of the high-grade utilization of the basement rooms and the terrain. This is why the injections had to be performed from just a few shafts with radially arranged bore holes (Figure 7). On the basis of the possible drilling accuracy (deviations of about ± 1% of the drilling length), the maximum drilling length was about 25 m and 30 m only in exceptional cases. One of the ten required injection shafts is illustrated in Figure 10, showing the drill fan for the stabilization. The planning of the drill fan was based on an effective injection radius of 0.75 m. To this we find corresponding an effective pore volume of about 35% of a theoretical injection quantity of about 60 l/m of boring.

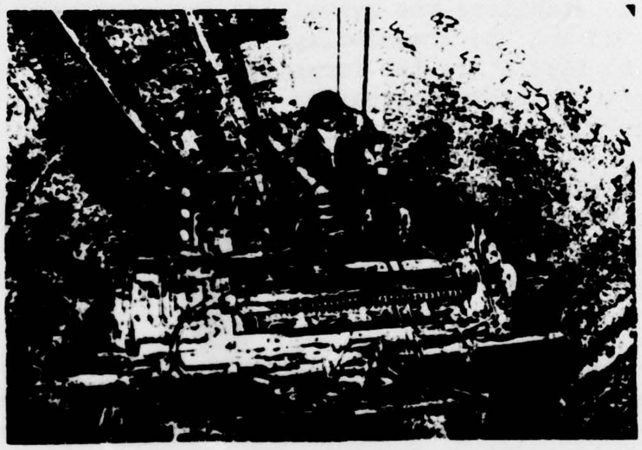


Figure 11. Injection Shaft With Drilling Equipment.

Figure 12. Injection Center, Guidance and Control Room.

Because the wells for underground water subsidence could not be built prior to stabilization due to the danger of destruction by injection, it was necessary to perform the stabilization with underground water still present. Because of the drilling method selected (Figure 11), this however did not result in any difficulties, for example, due to the collapse of the bore holes; to stabilize the bore holes, which would not be equipped with pipes, this method employed a bracing liquid made up of Bentonite cement. The injection bore holes as a rule were made with a diameter of 4-3/4". The drilled-out material was moved along with the bracing liquid which was constantly regenerated in a special sump at the bottom of the shaft by depositing the coarse part. At the completion of each bore hole, the PVC casing [sleeve] pipe with a diameter of 2" was built into that bore hole for the injection that would follow as the next step and it was then sealed.

Considering the scope of the stabilization work to be done here, it was necessary to build up an extensively automatically operating injection center (Figure 12) with all mixing and pumping systems as well as control mechanisms. The constant swelling controls formed the decisive criterion for the injection speeds. For this purpose, electrical contactors were attached in the basement at critical support columns, in addition to the leveling of the terrain and the buildings which was performed several times per day; these contactors indicated, optically and acoustically, whenever the predetermined, still harmless swelling tolerance of 5 mm had been reached. When this tolerance was reached, the injection was then interrupted and resumed elsewhere. To avoid a superposition of the injection pressure involved in different but simultaneously worked bore holes, three pumps were used per shaft. The sequence of pressed injection borings had to be so selected that the underground water would not be trapped in the soil.

The injection quantities were determined by means of the effective pore volume of the soil and were controlled via the pressing pressure. The average output attained during the work came to about 350 l/hr under the circumstances described, per pump [sic]. The work could be finished on schedule in spite of the situation encountered. The ultimately caused maximum swellings only came to 1.2-1.5 cm in the method described. The swelling differences between neighboring supports or walls came to about 1/3 of that and were harmless.

In this connection it must however be said that, because of the poor condition of the buildings, leakages of injection material into basement rooms, the swelling of basement floors, and the injection of old but no longer tightly sealed building drainage lines could not be avoided in spite of all precautions and care. But this damage could be reduced to a bearable minimum through constant observation.

In conclusion we must mention the fact that, in spite of the manner of execution selected for the stabilization, samples, taken from the injection shaft and the excavation ditches and pits, revealed strength figures between 25 and 45 kp/cm^2. The repeatedly required procurement of samples by means of

core drilling proved to be impossible in the soils encountered here.

It must therefore be recommended once again that the samples be taken generally from the excavation ditches or that the strength should be tested on the spot in order to rule out any misinterpretation of the stabilization.

4.4. Mining Drive With Injection Concrete Method, Construction Lot 6

. The last construction lot of the first phase of the rapid transit line--during which stabilization was also performed as a structural aid and safety measure--is construction lot 6.

The two parallel line tunnels in this construction lot were made according to the injection concrete method or the so-called "new Austrian construction method" with 7.7 m breakout [excavation] diameter, that is to say, they are driven according to the mining method in short thrusts (about 1.0 m) with parallel securing of the excavation intrados by means of injection concrete. The characteristic feature of this construction method is that here, at least during tunnel excavation, the stresses above the tunnel are supported not from the cutting area but from the construction underground itself via arches. In the area involved this requires a construction underground which facilitates arch formation. The loosely positioned gravels and sands above the tunnel located in "Frankfurt clay" however were no longer able to facilitate this at arch spans of 10-12 m.

The tunnels were driven from an approach shaft, stud on Mainzer Landstrasse from the direction of the main railroad station and, in the third part of the injection area provided, has a very small roof cover of about 8 m. After about 50 m of driving, the southern tunnel undercut the 11-story Hardy Bank Building whose foundation is located just above the gravel-clay boundary. The apex of the tunnel, at the most unfavorable point, is only 2.6 m below the underedge of the foundation. The gravel buffer here is only 1.44 m.

Under these circumstances, the formation of the desired protective arches above the only short thrusts of about 1.0 m, it was necessary to stabilize the loosely deposited gravel and sand. On the basis of static studies on the earth in the area, it was decided to stabilize up to 3.0 m above the clay horizon which is almost horizontal here according to the soil sample. Under the buildings, the upper edge extended to the lower edge of the foundations.

Because the stabilization zone was located under the houses involved and partly under Mainzer Landstrasse, it was necessary here again to provide stabilization in the radially arranged fans from injection shafts. Here a strength of 5 kp/cm^2 was enough because the consolidated cover layers were not cut. Stabilization was accomplished with gel on a soda-waterglass space. It was necessary to stabilize about 8,254 m^3 of soil on a surface of about 2,690 m^2.

5. Summary

The above article shows, on the one hand, what static studies on the surrounding earth and what soil mechanics investigations must be performed prior to the decision as to the implementation of injections. It was shown that stabilization, in cases such as these, becomes effective mostly via arches and that, for this reason, the stabilization bodies must be dimensioned with a view to these arches. In the case of the construction measures involved here and the underground conditions, it furthermore turned out that the arches could be formed only over shorter spans and that large-area settlement depressions therefore could not be prevented.

Finally we can observe that the stabilization itself can be performed under even the most difficult conditions in terms of construction management and that it can be guaranteed in terms of its quality. The prerequisite here however is that it must, as in our case, be planned carefully down to the last detail in cooperation with the client before construction work is started. The benefit to be derived from expensive stabilization however can be measured by the fact that, in the actual tunnel construction work, in general, there were no dangerous settlement defenses which, in the existing, settlement-vulnerable buildings above ground, could have led to structural damage.

BIBLIOGRAPHY

1. Keckeisen, W.: "Some Construction Methods Used in the Construction of the Rapid Transit Lines and the Frankfurt/M. Airport Line," Der Eisenbahn-ingenieur [The Railroad Engineer], No. 21, 1970, pp 83-87.

2. Eule, K. H.: "Railroad Engineering Problems During Rapid Transit Line Construction in the Area of the Frankfurt/Main Railroad Station," Forschung + Praxis [Research and Practice], Volume 12, Modern Tunnel Construction.

3. Schmaus, W. and Glock, H.: "The Frankfurt Rapid Transit Line--First Phase," Die Bautechnik [Construction Technology], No. 10, Volume 51, pp 325-332.

4. Cambefort, H.: Injection des sols [Soil Injection], Paris, 1964.

5. Jähde, H.: Injektionen zur Verbesserung von Baugrund und Bauwerk [Injections to Improve the Construction Underground and the Structure], Berlin, Technik publishers, 1953.

6. Haffen, M.: "Treatment of Cohesionless Soils With Colloidal and Liquid Injection Materials," lectures at the 1964 Construction Underground Conference, Berlin, German Society for Earthwork Engineering and Underground Construction, Essen.

7. Kutzner, Ch.: "On the Mechanical Properties of Earth Materials Injected

With Silicate Gel," Die Bautechnik, Volume 45, No. 3, 1968.

8. Leussink and Müller-Kirchenbauer, "Investigations on the Injection of Solid Substances Into Core Systems With a View To the Injection Technique," lectures at the 1966 Construction Underground conference in Hamburg.

9. Maag, E. and Brun, A.: "Injection Methods as Construction Methods," Schweizerische Bauzeitung [Swiss Construction Journal], Volume 71, No. 37, 1953, pp 533-536.

10. Grundbau Taschenbuch [Underground Construction Pocketbook], Volume I, 2nd Edition, pp 971-981, Berlin, Ernst & Sohn, publishers, 1968.